FINE STRUCTURES OF SOLAR RADIO BURSTS AND NOISE STORMS

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Abstract

A review is given about fine structures detected by spectrographic observations which still constitute a violantly evolving field of solar and cosmic radio astronomy. Common and peculiar features of fine structures in the major types of sporadic solar radio emission, viz. continuum bursts, drift bursts, and noise storms, are briefly discussed. Fast drift bursts, indicating particle acceleration and forming a main spectral type of solar burst emission, are also attributed to other burst types (e. g. type II–bursts) and decametric storm radiation. Improved methods of observation provide a rising number of still unclassified fine structure elements; a brief survey of such furthergoing features is added. The possible emission mechanisms available are shortly mentioned including relationships to planetary radio phenomena.

1 Introduction

During the last two decades the quality of solar radio observations has been greatly improved, especially with regard to spectral and spatial resolution. Therefore it is not surprising that a lot of fine structures were detected, not all of them could be explained physically up to now.

In this paper we shall restrict our considerations on the cases of *temporal* and *spectral* features; a discussion of *spatial* fine structures would need a separate review and will be excluded here. Before going into more detail in describing burst fine structures it may be useful to make some remarks about the classification of solar radio emission in general.

With respect to their temporal variation since the first systematic observations we learned to distinguish between the relatively stable quiet background component (T $\sim$ 11 years), the slowly varying component (S–component, T $\leq$ 27 days), and the sporadic component with a great variety of burst types lasting between seconds and hours.

With respect to bursts spectral classifications can be made. So it is customary to subdivide the radiation roughly into a microwave part and a meter–wave part; or, more precisely,

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into the mm– and cm–waves for the first case, and into dm–, m–, Dm–, and Hm–waves for the latter one. The most common and, as we shall see later, a very useful graphic representation of the solar radio emission is the so–called *dynamic spectrum*, a frequency–time–diagram of the radio flux density (spatially integrated intensity). Three examples of such a diagram are schematically represented in Figure 1, where the typical burst types may be recognized.

Although this kind of display contains no information about the spatial distribution of burst events over the solar disk, it may be an invaluable tool for recognizing the underlying physical processes and plasma parameters. Because of the relationship between emission frequency and source height in the solar corona ($f \simeq f_p \sim \sqrt{\mathrm{N}}$ decreasing with height), the position in the diagram indicates the approximate height level and – in the case of drifting phenomena – additionally the propagating velocitiy of the burst exciter.

The 'classic' classification of the different spectral burst types was introduced by Wild and McCready [1950]. This more historical than logical classification scheme uses roman numbers for the characterization of bursts (type I to type V bursts with some later introduced subclasses).

2 Continuum Bursts

In contrast to the relatively narrow–banded drift bursts (cf. next section) the so called continuum bursts are in general more extended in both, the frequency and the time domain (i. e. they cover a larger area in the dynamic spectrum). An often observed 'gap' in the dm–region leads to a separation into the *microwave bursts* and *meter–wave bursts.*

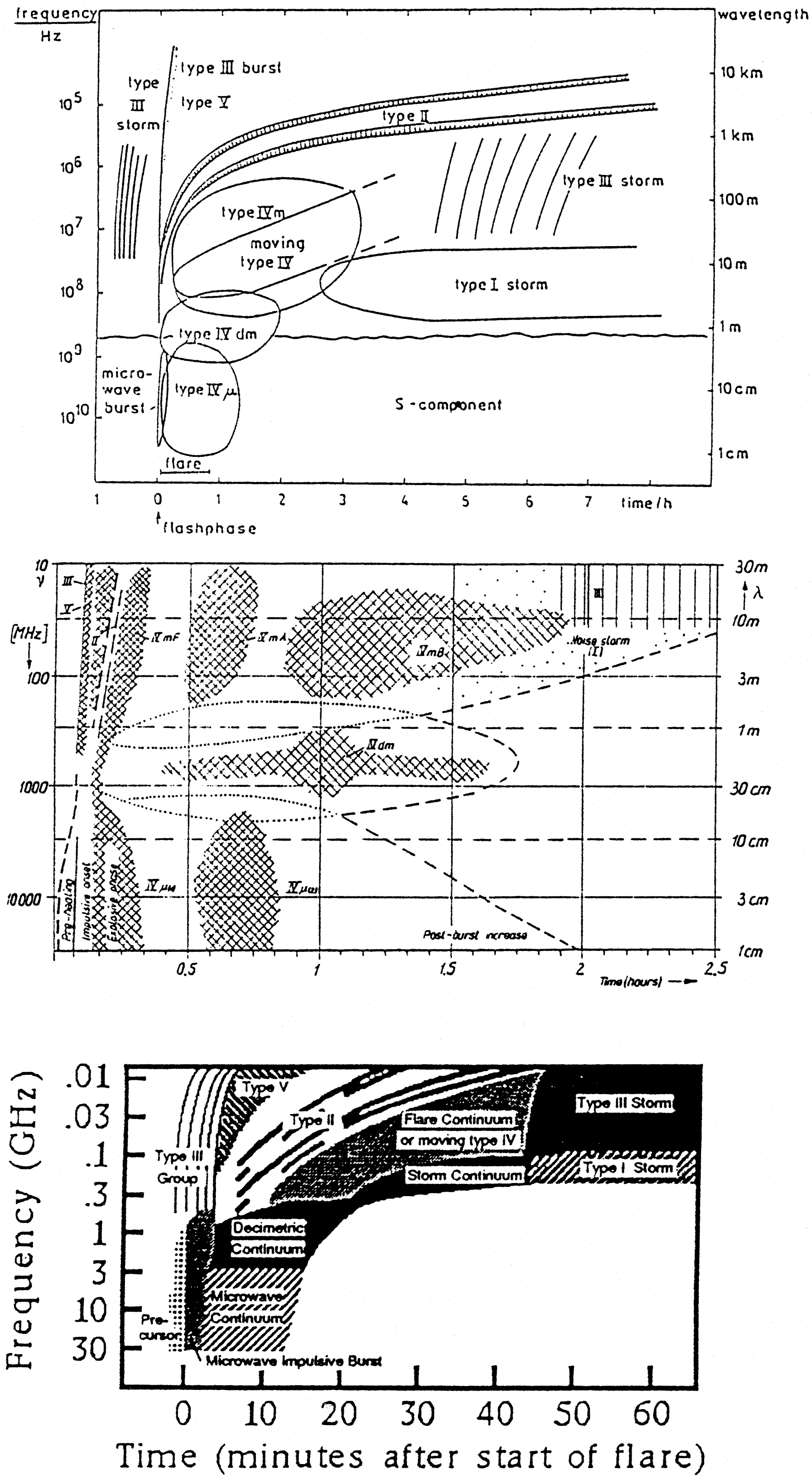
2.1 Microwave Bursts

Bursts in the cm–range are caused mostly by gyroemission of accelerated particles in the lower corona above sunspot groups. For many years they were found to be the simplest burst type as Kundu [1965] wrote : *'They are characterized by a rapid rise in intensity usually followed by a slower decline. The burst–radiation is rather smooth, free of details in time and frequency ...'* Considering the large number and variety of microwave fine structure elements which have been observed and discussed in the literature during the last two decades it is obvious that this valuation has to be changed.

Our nomenclature for this section is based on the paper by Allaart et al. [1990], which seems to represent the latest (but not yet confirmed) stage of knowledge in this subject.

We can devide microwave features into *temporal* fine structures (e. g. 'millisecond spike bursts') observable at single frequencies and *spectral* features as mentioned in the following list, which are detectable only with highly resolving spectrographs.

a) *Microwave Blips*
   Most common fine structures, firstly noted by Benz et al. [1981]. Their main



Hildebrandt (1983) adapted from Rosenberg (1976)

Krüger (1979)

Gary (1991) adapted from Dulk (1985)

Figure 1: Three examples of schematic representation of the dynamic radio spectrum such as might be seen during a large flare. The different types of emission are labeled and described further in the text.

characteristics are: Low intensity (tens of solar flux units (1 s.f.u = 10^{-22} $\mathrm{W\,m^{-2}\,Hz^{-1}}$)), short single–frequency lifetime (about 100 ms), drift rates between 2 and 20 GHz s^{-1}, and in most cases weak polarization.

b) *Slow Drift Blips*
Major differences to a) are longer lifetime, slower drift, and higher intensity.

c) *Hands*
The shape of these events in the spectrogram looks like a hand with outstreched fingers.

d) *Dots*
They consist of a number of short–lived emissions with a small bandwidth, often occurring in chains with a well–determined drift.

e) *Tartan Structure*
Quasi–periodic structures with opposite drifts, a total duration of some hours, and drifts from -1.6 GHz s^{-1} to 1.6 GHz s^{-1}.

Furthermore, there were observed such phenomena as *fast drifting blips*, *fringe phenomenon*, and *switch–on–switch–off–structures (SOSOS)*. It would be beyond the scope of this paper to evaluate all these strange fine structure elements; only some general properties should be given:

- Short duration (down to some ms at single frequencies),
- intensity ranges from some s.f.u. (a, d) to a few hundred s.f.u. (b, c),
- drifts from 0 to 20 GHz s^{-1} (a),
- no (b) or only weak polarization.

A detailed description illustrated with a large number of observed examples is given in Allaart et al. [1990] as mentioned above.

2.2 Type IV–Bursts

Type IV bursts are one of the most complex phenomena in solar radio emission. This is reflected by a large number of different sub–classes, as type IVcm, type IVdm, type IVmA, type IVmB, moving type IV etc., occurring at different wave lengths at different phases of a flare event.

More details about the general properties of this kind of burst can be found in Krüger [1979], McLean and Labrum [1985], and – especially in view of fine structures – in Slottje [1981].

The most abundant fine structures in type IV events are pulsating structures, fiber bursts and zebra patterns. Much less abundant are spike bursts and braided zebra patterns, whereas tadpole bursts are extremely rare (if real at all).

- **Pulsating structures**

  Pulsating structures were described as series of fast drift bursts in the meter–wave range (cf. e.g. Kundu [1965]). But higher resolved observations reveal that a considerable part of them consists of series of *broad–band short–lived absorption pulses* (B.S.A. pulses). The word 'absorption' is not used here in its original physical meaning, it might be understood more as an interruption of the emission process (therefore the name *sudden reductions* can also be found, cf. e. g. Kuijpers [1975] and Slottje [1981]). A recent review about the theory of radio pulsations was given by Aschwanden [1987].

- **Fiber Bursts**

  Fiber bursts are *'intermediate drift bursts'* in the dm–region with mostly 'normal' (that means negative) drift rates between 10 and 50 MHz s^{-1}. They were observed to appear in groups of some tens of members during one event and have typical frequency ranges between 200 and 500 MHz. The intrinsic bandwidths and durations of the fiber bursts are about 1.5 MHz and 0.3 s, respectively. At the low–frequency side an absorption edge of the same extent is frequently observed.

  Fiber bursts are an important tool for determining plasma parameters, especially the magnetic field strength in the type IV burst source.

  Various attempts were made to interprete this burst type as a radio signature of whistler solitons [Kuijpers, 1975], localized formstable whistler wave packets [Mann et al., 1987], or of kinetic Alfvén solitons [Treumann et al., 1990].

- **Zebra Patterns**

  Zebra patterns (sometimes also referred to as *'spaghetti structures'*) consist of several almost parallel drifting stripes of absorption and emission (therefore they are also called *parallel drifting bands*). Because the stripes are not always completely parallel and also disappearing and new arising lines exist, the latter name seems to be not correct. Sometimes a confusion (or common classification) with fiber bursts can be found in the literature.

- **Spike Bursts and Flash Bursts**

  - A number of short–lived bursts have been called spike bursts or flash bursts, where – according to Slottje [1981] – the first ones are associated with type IV and type III burst activity and the latter ones with type I storms and type IV mB bursts.
  - Flash bursts have durations of ≤ 0.1 s and bandwidths of about 20 to 40 MHz.
  - Spike burst events are relatively rare phenomena, their intensities can reach several tens of s.f.u., i. e. they are much stronger than flash bursts. The duration of the whole event is about 1 min, the half power duration of the spikes would be 0.05 s or less with bandwidths generally smaller than 3 MHz (in extreme cases more than 10 MHz or much less than 1 MHz).
  - They are generally circularly polarized.

In addition to the above enumerated fine structures there exist a lot of modifications, some very rare phenonena, and even (but very few) unclassified structures. Only for completeness, such phenomena as *braided zebra patterns, tadpole bursts, tadpole zebra patterns, quasi fiber bursts, and drifting spikes* should be mentioned here to demonstrate the great variety of structures as well as their close connection to zoology.

3 Drift Bursts

The second large class of bursts are the so called drift bursts, which are characterized by a narrow band width and a more or less clearly distinct frequency shift with time. Depending on their different exciters (which lead to different propagation velocities) we distinguish between fast drift bursts (type III and related types) and slow drift bursts (type II).

3.1 Fast Drift Bursts

Type III bursts are caused by accelerated electrons in the lower corona (‘particle beams’) which travel with sub–relativistic velocities (0.2c $\leq$ v $\leq$ 0.6c) out through the corona along magnetic field lines. The interaction with the surrounding plasma leads to the generation of Langmuir waves which – by scattering processes – later in turn generate electromagnetic waves at the local plasma frequency f_p and sometimes at its first harmonic $2f_p$.

They show a very rapid frequency drift from high to low frequencies, where the drift rate df/dt is roughly 100 MHz s^{-1} in the meter–wave range (some 100 times faster than other drifting phenomena) decreasing with decreasing frequencies. (As mentioned above, the ‘normal’ drift rate is negative. Therefore, the minus sign is often omitted, except when ‘opposite’ (or ‘reverse’) drift occurs.)

Often type III bursts can be observed from $\sim$ 1 GHz down to the lower frequency limit of ground–based observations ($\sim$ 10 MHz) and further, by spacecraft observations, down to $\sim$ 10 kHz, which shows that the streams (and so Langmuir waves too) exist not only in the solar corona but also in the interplanetary space.

More specific properties, such as flux densities, polarization, abundance, correlation to other events, etc. can be found in Krüger [1979] or McLean and Labrum [1985]. In this paper, only some important fine structures and modifications of the ‘standard type III’ should be briefly mentioned.

- **F–H Pairs**

  As already mentioned above, in a small fraction of type III bursts harmonic structure can be observed, that means, there is a splitting into two frequency lanes where the ratio of harmonic to fundamental averages $\sim$ 1.8 : 1.

- **Inverted–U Bursts**

  These events are starting as a normal type III burst, but then the frequency drift stops and later reverses, so that its shape in the dynamic spectrum is similar to an inverted 'U'.

  The interpretation of such a behavior could be that the electron stream is accelerated along a magnetic arch which guides the source of emission first to the top and then back down to the other leg of the arch.

- **J Bursts**

  Similar to inverted–U bursts, except that the return stroke is faded out.

- **Type IIIb Bursts**

  In a small part of type III bursts the radiation is not a smooth function of frequency but contains fine structure. These fine structure components are known as *split pairs* and *stria bursts*, and then the envelope is called *type IIIb* (see Figure 2).

- **Type V Bursts**

  Type V bursts appear as diffuse continua following certain type III bursts or burst groups, especially in the long–meter wavelength region. They have longer durations (a few minutes) at lower frequencies and show in most of the cases an opposite sense of polarization compared with that of the preceding type III event. For more information about this see McLean and Labrum [1985].

- **Herringbone structures**

  In connection with type II bursts, sometimes a large number of type III bursts can form herringbone–like patterns (see next section).

3.2 Slow Drift Bursts

Slow–drift bursts are outstanding phenomena often connected with large flare events (starting 2–15 min after the flare) and occur much less frequently than fast drift bursts.

Type II bursts are very intense events ($\mathrm{S_f} \leq 300000$ s.f.u. which would give $\mathrm{T_b} \sim 10^7 - 10^{13}$ K if thermal emission is assumed) with a frequency extension from about 150 (500) MHz down to 20 (0.1) MHz (extreme cases in parentheses) and drift rates between 0.25 and 1 MHz s^{-1}. Such frequency drift can be interpreted as propagation of the travelling disturbances outward through the corona, similar to type III bursts, but with comparably lower velocities ranging between 200 and 2000 km s^{-1}. Since these velocities are remarkably greater than the coronal sound speed and Alfvén velocity, MHD shock waves must play a role inducing Langmuir waves and plasma emission (which is well accepted in principal, but not clear in detail). It is not the aim of this paper to discuss such questions, only some specific fine structures should be demonstrated.

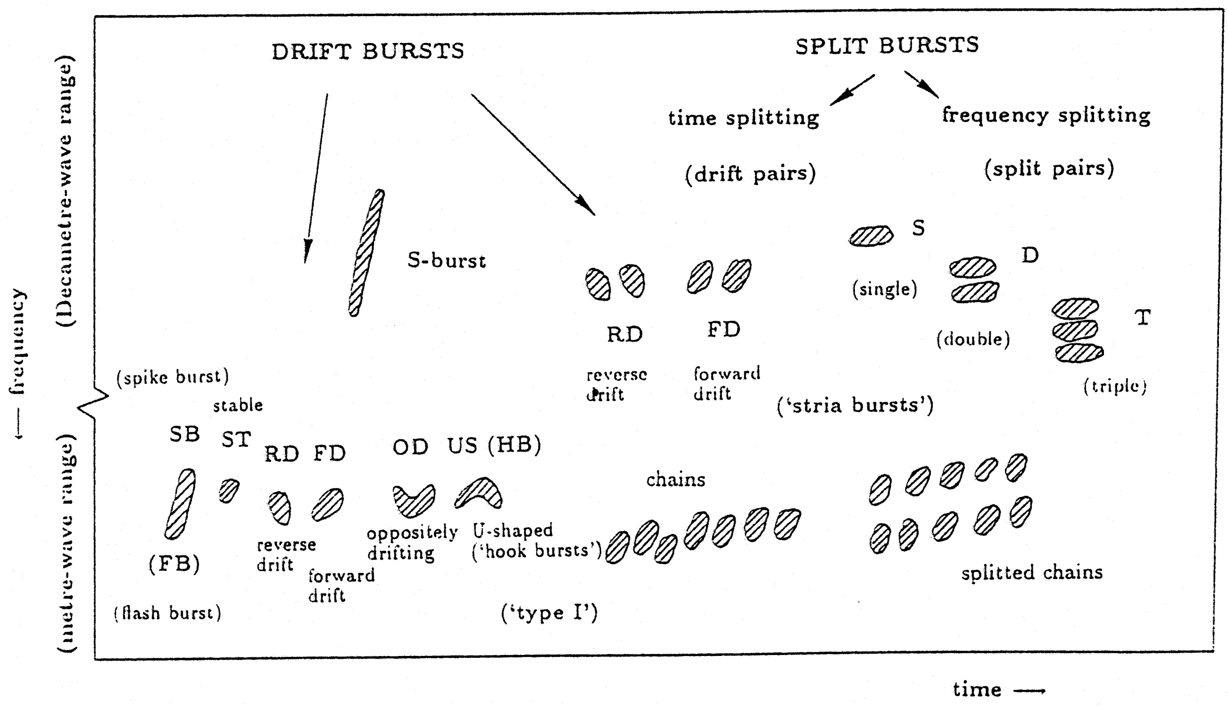


Figure 2: Schematic representation of different possible fine structure elements occurring in solar noise storms.

- **Harmonic Structure**

  Similar to type III bursts, the structure of slow drift bursts is often ($\sim$ 60% of all events) determined by the existence of narrow–banded harmonic lanes ($f_H/f_F \leq 2$; the indices correspond to 'harmonic' and 'fundamental', respectively).

- **Frequency Splitting (Band splitting)**

  Each harmonic lane can be doubled once more into two separated bands with about 10 % of the band midfrequency.

- **Multiple lanes**

  In some bursts there are several drifting bands ('lanes') which are neither harmonically related nor consistent with simple band splitting.

- **Herringbone Structures**

  Certain type II bursts exhibit this feature which is determined by a lot of positive and negative fast drift bursts emerging from both sides of the ridge ('backbone') of the slow drift element. Sometimes the 'backbone' is entirely absent and only the rapidly drifting components are visible.

  Herringbone bursts often show a very low drift rate. This may imply that the shock wave moves nearly parallel to the solar surface.

4 Noise Storms

Noise storms consist of long lasting (ranging from a few hours to even several days) radio continua in the m–Hm–wave region superimposed by thousands of short–lived spikes (type I storms in the meter–wave region and/or type III storms in the Dm–/Hm–wave region). Both are correlated, which led to the assumption that they have the same origin.

General properties of storm bursts are:

- narrow bandwidth,
- high directivity,
- circular polarization in the O–mode.

A necessary (but not sufficient) condition for the occurrence of noise storms is the existence of strong magnetic fields (i. e. big active regions).

Concerning the emission mechanism of this burst type it seems only clear that it is some kind of fundamental plasma emission (the high brightness temperatures and O–mode polarization could not be explained otherwise).

Fine structures or special features, occurring in storm bursts, are:

- type I chains,
- drift pair bursts,
- stria bursts,
- S–bursts (‘fast drift storm bursts’).

These features are schematically represented in Figure 2. It should be noted that some of these fine structures occur also in other frequency ranges or in connection with other burst types (see e. g. type III bursts).

With respect to planetary emissions it is worth to mention, that the last phenomenon of the foregoing list, the ‘fast drift storm burst’ was given the alternative name ‘S–burst’ by McConnell [1982] because of its analogy to this class of Jovian bursts.

More details about noise storms can be found in Elgarøy [1977], Krüger [1979], and McLean and Labrum [1985].

5 Final remarks

Although this review about *spectral* and *temporal* fine structures in solar radio emission is very brief and only some details could be listed, it can be extracted from the foregoing sections that the number and variety of features is enormous and a lot of work is still to be done to find a satisfactory interpretation and physical classification for all these phenomena.

From our point of view, the following conclusions can be outlined.

- The main basic *emission processes* for solar radio bursts, namely
  - gyrosynchrotron emission,
  - plasma radiation,
  - cyclotron maser instability

  also occur in planetary magnetospheres.
- The study of spectral fine structures is evolving in *solar* and also in *stellar physics* ('flare stars'!).
- Further progress in the interpretation of radio phenomena depends on a *combination* of observations with high *spatial, spectral,* and *temporal* resolution.
- The following features seem to be especially important for theoretical progress:
  - *Spike bursts* may be deciding for the study of energy fragmentation in flare processes ('micro–/nano–flares').
  - The analysis of *frequency drifts* is essential for the examination of flare dynamics and ∼ scenarios, e. g.
    - collisionless conduction fronts,
    - reconnection in elementary flux tubes,
    - coalescence of current filaments,
    - Ohmic and anomalous current dissipation,
    - dissipation of wave energy,
    - shock–wave acceleration of particles.
- Some spectral fine structures need *verification* by more and independent measurements.
- The *diagnostic capability* must be further developed for both, observation and theory.

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